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Key Points:

- Streamflow and EC responded during all events in a degraded grassland catchment but only during large events in a reforested catchment
- The EC-based maximum event water fractions increased with event size and maximum precipitation intensity
- The space-for-time approach suggests that reforestation can change the hydrological flow pathways and improve hydrological functioning

Supporting Information:

- Supporting Information S1
- Date Set S1

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Effects of Reforestation of a Degraded *Imperata* Grassland on Dominant Flow Pathways and Streamflow Responses in Leyte, the Philippines

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Abstract Reforestation of degraded grasslands can increase the soil hydraulic conductivity and number of preferential flow pathways. However, it is not clear to what extent these changes affect streamflow responses and whether this depends on the event size. We, therefore, studied the hydrological response of two small catchments near Tacloban, Leyte (the Philippines): a degraded *Imperata* grassland catchment and a catchment that was reforested 23 years prior to our study. Precipitation, stream stage, and electrical conductivity were measured continuously from June to November 2013. Samples were taken from streamflow, precipitation, groundwater, and soil water for geochemical and stable isotope analyses. Streamflow and electrical conductivity changed rapidly during almost every event in the grassland catchment, but in the reforested catchment, these responses were much smaller and only occurred during large events. Streamflow was a mixture of groundwater and precipitation for both catchments, but the maximum event water contributions to streamflow were much larger for the degraded grassland than for the reforested catchment. The differences in the event water contributions and timing of the streamflow responses were observed across all event sizes, including a large tropical storm. Together with the low saturated hydraulic conductivity in the degraded catchment, these results suggest that overland flow occurred more frequently and was much more widespread in the degraded grassland than in the reforested catchment. We, therefore, conclude that reforestation of a degraded grassland can change the dominant flow pathways and restore the hydrological functioning if the forest soil is allowed to develop over a sufficiently long period.

Plain Language Summary It is not clear yet to what extent reforestation of degraded tropical grasslands changes the response of streams to rainfall events and whether this depends on the size of the event. We, therefore, studied two small catchments near Tacloban, Leyte (the Philippines): a degraded grassland catchment and a catchment that was reforested 23 years prior to our study. Streamflow and stream water chemistry changed rapidly during almost every rainfall event in the grassland catchment, while in the reforested catchment, these responses were much smaller and only occurred during large rainfall events. Together with the slow rate with which water can infiltrate into the soil, these results suggest that water flowed more frequently over the soil surface and this overland flow was much more widespread in the grassland catchment than in the reforested catchment. The differences in the maximum fractions of rainfall in stream water and the timing of the streamflow responses were observed for all events, including a large tropical storm. This indicates that the pathways that the rain takes toward the stream have changed as a result of reforestation. We, therefore, conclude that reforestation of a degraded grassland can improve streamflow regulation if the forest soil is allowed to develop sufficiently.

1. Introduction

Swidden cultivation (i.e., slash-and-burn agriculture) can be a sustainable practice (Brady, 1996; Sauerborn, 1994), but when fallow periods become critically shortened due to increased population pressure, the repeated fire can lead to unproductive fire-climax grasslands dominated by *Imperata* and *Saccharum*. Garrity et al. (1996) estimated that the total area under *Imperata* grassland in South and Southeast Asia alone was about 35×10^6 ha in the early 1990s but also noted that this was likely an underestimation.

Imperata grasslands can have poor soil physical characteristics, such as low infiltration capacity, especially when grazed (Snelder, 2001). Surface runoff on degraded grasslands often causes severe erosion, which together with increased landsliding leads to water quality problems (Trustum et al., 1999; White, 1996). In the Philippines, *Imperata* grasslands are known as *cogon* and covered more than 6.5×10^6 ha in 1990, of which two thirds were characterized by moderate to severe erosion (Concepcion & Samar, 1995). Partly in response to such problems, the “National Greening Program” of the Philippines aimed to plant 1.5 billion trees on 1.5×10^6 ha of degraded land (much of it under *cogon* and shrub) in 6 years (Aquino & Daquio, 2014). However, the hydrological impacts of reforesting degraded land remain understudied and are largely undocumented (Scott et al., 2005). Understanding how runoff generation mechanisms and streamflow responses change after reforesting degraded land is important to understand the downstream impacts of large-scale reforestation projects (Liu et al., 2015; Trimble et al., 1987; Zhou et al., 2010). In places like the Philippines, where tropical storms and typhoons are common, it is particularly important to study how reforestation affects runoff processes for very large events because nearly a third of all precipitation is derived from typhoons (Cinco et al., 2016), and their intensity is expected to increase in the future (Balaguru et al., 2016).

Numerous paired catchment studies across the globe have shown that (re) forestation typically results in decreases in annual water yield and dry season flows due to increased evaporative losses, whereas forest clearing typically results in increased flows (Bosch & Hewlett, 1982; Buytaert et al., 2007; Farley et al., 2005; Iroumé et al., 2005; Jones & Post, 2004). In a global analysis of experimental studies, Jackson et al. (2005) and Farley et al. (2005) showed that forestation of grassland and shrubland decreased streamflow (mostly baseflow) on average by 180 mm/year or 38%. However, these data sets included few tropical sites, and results from temperate forests are not necessarily transferable to the tropics, where soils are different and precipitation is more intense (Bonell et al., 2005; Wohl et al., 2012). Furthermore, degraded sites, where the dominant hydrological processes likely differ from those in controlled experiments (Bruijnzeel, 1989; Malmer et al., 2010), were not included in these global analyses. When soils are not disturbed much, the relative effects of forest removal tend to decrease as event total precipitation increases and are often not detectable for the most extreme events (Beschta et al., 2000; Hewlett, 1982; Hsia, 1987; Levy et al., 2018) because the relative effects of changes in soil and canopy storage capacity are smaller for these large events (Scott et al., 2005). This is particularly the case for sites with shallow soils (Birkinshaw et al., 2011). However, land degradation may lead to large changes in flow pathways, so that differences may persist even for the largest events (Scott et al., 2005). Lana-Renault et al. (2014) documented very large differences in peak flows for a forested, an abandoned agricultural, and a badland catchment in the Pyrenees, suggesting that differences in peak flows and runoff ratios may exist for all event sizes if the soils are degraded. Yet, so far, there is very little data to determine how reforestation of degraded tropical grasslands affects runoff responses and runoff generation mechanisms for small and large events.

Land degradation typically results in a sharply reduced surface field-saturated hydraulic conductivity (Lal, 1996; Toohey et al., 2018; Ziegler et al., 2006; Zimmermann et al., 2010) and infiltration because declines in organic matter, exposure to raindrop impact, surface sealing, and compaction by cattle or machinery (Malmer et al., 2010) lead to fewer large pores and less preferential flow (Deuchars et al., 1999). In extreme cases, this may lead to reduced groundwater recharge and, ultimately, declined dry season streamflow (Bruijnzeel, 1989). Natural regrowth or reforestation of degraded land may restore the near-surface hydraulic conductivity and soil hydrological functioning within one to two decades (Bonell et al., 2010; Godsey & Elsenbeer, 2002; Hassler et al., 2011; Zimmermann et al., 2010; Zimmermann & Elsenbeer, 2009; Zwartendijk et al., 2017), suggesting that overland flow can be reduced and become less widespread during forest maturation (Chandler & Walter, 1998; Krishnaswamy et al., 2012; Zhou et al., 2002). However, actual flow pathways and infiltration rates likely differ from those inferred from point-scale hydraulic conductivity measurements (Chappell & Sherlock, 2005; Sherlock et al., 1996; Vigiak et al., 2006) because of surface sealing (Rao et al., 1998) and macroporosity (Chappell, 2010).

Data from runoff plots on karst terrain in the Philippines indicated that the threshold for overland flow occurrence for a pasture fallow was only 4 mm during wet initial conditions and 28 mm during dry initial conditions, whereas the threshold for a forested plot was 95 mm (no differentiation between wet and dry initial conditions possible; Chandler & Walter, 1998). The surface runoff ratios were also different (76% for the pasture fallow vs. 3% for the forest). Toohey et al. (2018) showed based on sprinkling experiments

on small plots on volcanic soils in Costa Rica that overland flow and lateral flow were the dominant runoff processes in a pasture, whereas storage and percolation were the dominant processes in the forest. Overland flow was 14–32% of applied precipitation for the pasture and <5% for the forested plots (Toohey et al., 2018). Zhou et al. (2002) showed for three microcatchments on laterite soils derived from granite in China that stormflow volumes were highest for a bare land catchment (10% of precipitation), intermediate for a Eucalyptus catchment (6%), and almost negligible for a mixed forest catchment (0.02%). The sediment losses from the bare land catchment were also much higher than for the reforested catchments, suggesting that reforestation reduced overland flow amounts and kinetic energy.

Isotope-based hydrograph separation can be used to determine the contributions of event water (“new” water: overland flow and precipitation) and pre-event water (“old” water already present in the catchment: groundwater and soil water) to streamflow at the catchment scale (Buttle, 1994; Klaus & McDonnell, 2013). Isotope hydrograph separation is widely used to study runoff generation mechanisms in temperate forested catchments but has remained underutilized in the tropics (Buttle & McDonnell, 2005). Using stable isotopes, Liu et al. (2011) showed that event water contributions were much higher for a rubber plantation than in a nearby rainforest, which they interpreted to be the result of much more widespread overland flow in the plantation. Isotope hydrograph separation results for a forested, a reforested, and a heavily grazed catchment in Mexico suggested that runoff generation was dominated by subsurface flow in all catchments but that for the largest event (with a 2-year return interval), event water contributions were much larger for the grazed catchment than for the forested catchment, indicating substantially more overland flow for the grazed catchment during this large event (Muñoz-Villers & McDonnell, 2013).

Geochemical-based hydrograph separation and End Member Mixing Analysis (Barthold & Woods, 2015; Hooper et al., 1990) have been used in multiple studies in tropical settings to determine the contributions of different source waters to the stream (e.g., Bruijnzeel, 1983; Elsenbeer et al., 1995; Kurtz et al., 2011; Scholl et al., 2015). For instance, a hydrochemical study of two ephemeral streams in southwestern Amazonia on Precambrian basement rocks (granite and gneiss) showed that the runoff ratio was very small for an old growth forest microcatchment (0.8%) and streamflow during rainfall events consisted mainly of throughfall (57%), groundwater (24%), and shallow soil water (19%), but runoff ratios were much larger for a pasture (17%), where the dominant streamflow components were overland flow (60%), groundwater (35%), and soil water (5%; Chaves et al., 2008). Isotope and silica data from catchments with Acrisols on predominantly rhyolitic and rhyodacitic rocks in southern Brazil suggested that in a forested catchment stormflow consisted mainly of rapid subsurface flow and macropore flow, while in an agricultural catchment stormflow was mostly due to overland flow (Robinet et al., 2018).

While these previous isotope and geochemical studies showed that overland flow is common and more widespread in agricultural or pasture catchments than forested catchments, they cannot be directly used to understand the hydrological effects of reforestation of degraded grasslands. Therefore, this study compares the runoff response of a degraded *Imperata* grassland catchment (Basper) with that of a semimature reforested catchment (Manobo) on the island of Leyte (the Philippines) to determine (i) the effect of reforestation on the magnitude of the runoff response, fraction of event water in stormflow, and the dominant flow pathways and (ii) how these are affected by event size.

2. Study Sites

In order to study the effects of reforestation of degraded *Imperata* grasslands on dominant runoff pathways and streamflow responses, we used a space-for-time approach and instrumented two small headwater catchments near Tacloban, NE Leyte, the Philippines (Figure 1). The Basper catchment is a 3.20-ha degraded grassland catchment (11°15'N and 124°57'E) that was last burned in 2006. The vegetation consists of cogon grass (*Imperata cylindrica*), mixed with sedges (*Cyperus* sp.) in poorly drained areas (both knee to hip height) and with shrubs (<1.5 m high; mostly *Melastoma malabathricum* and *Chromolaena odorata*) on midslope sites. Shrubs and small trees (2–3 m high; mostly *Neonauclea lanceolata* and *Leukosyke capitella* and a few remnant planted *Acacia mangium*) are common along the stream, covering ~14% of the catchment area. Landslide scars are also common and covered ~3.4% of the catchment area (Zhang et al., 2018). Except at the landslide scars, vegetation covers the soil in almost all of the catchment. The streams are incised into the weathered Gabbro and are typically less than 1 m

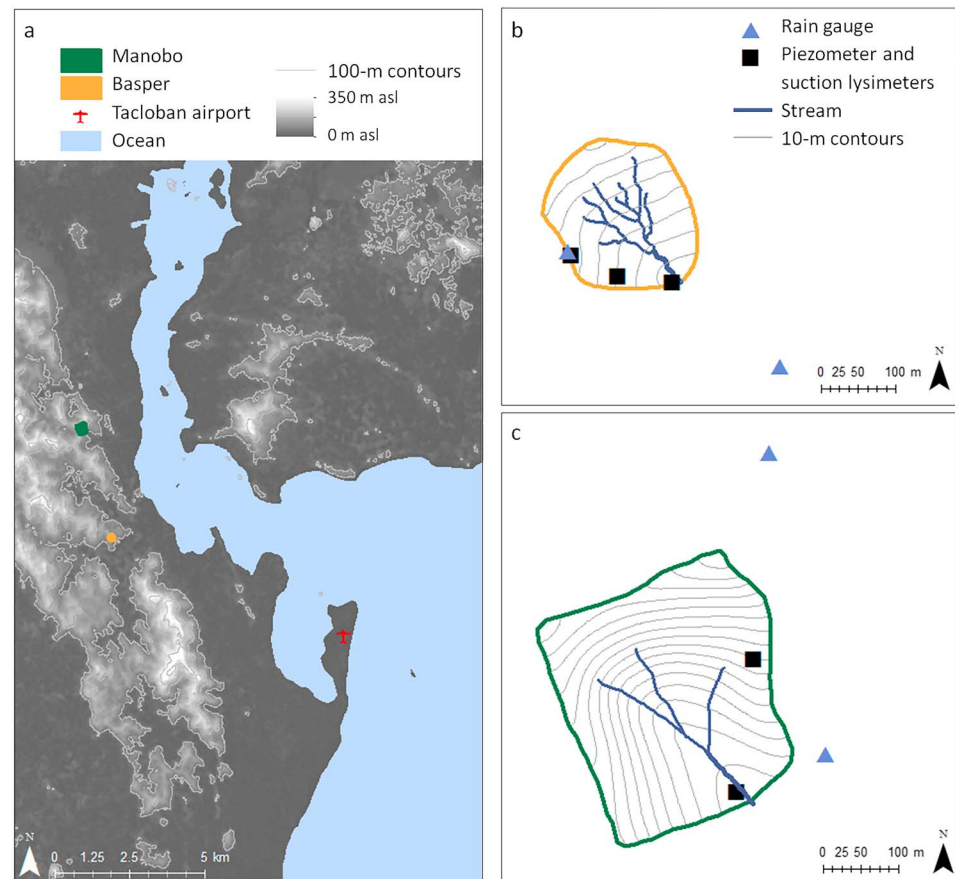


Figure 1. Location of the two study catchments (in green and orange) relative to Tacloban airport (in red), with the elevation and 100-m contour lines starting at 50 m (a) and the main measurement locations in the Basper degraded grassland catchment (b) and the Manobo reforest catchment (c) with 10-m contour lines.

wide. Seeps were observed at the contact between the weathered rock and the fresh rock or between the soil and weathered rock—all just above the streambed.

In the 8.75-ha Manobo catchment (11°17'N, 124°56'E), reforestation of the degraded grassland started in 1990 when the Manobo tribe relocated to the area. First, *Gmelina arborea* and mahogany (*Swietenia macrophylla*) trees, as well as coconut palms (*Cocos nucifera*), were planted to shade out the *Imperata* grasses, after which other plants and trees, including almond, papaya, banana, and medicinally useful plants and rattans were planted (U. Padecio, personal communication, June, 2013). During the time of this study, the forest consisted of a mixture of planted trees and naturally regenerating species. A 1,850-m² plot contained more than 50 different tree species; average canopy height was 7.3 m, and the basal area was 15 m²/ha. The average Leaf Area Index (measured 12 times at 24 sampling locations before Typhoon Haiyan damaged the canopy in November 2013) on a midslope plot was 5.1 ± 0.65 . Average interception loss prior to canopy damage was 19.6% (Zhang, Bruijnzeel, van Meerveld, et al., 2019). Near the gauging station, the banks were near vertical and up to several meters high. Numerous seeps were observed at the contact between the soil and the fractured and weathered rock just above the streambed. The shallow gullies in the upper part of the catchment were filled with eroded material and only contained water during large events.

The space-for-time substitution approach used in this study assumes that the two catchments had a similar runoff response prior to reforestation of the Manobo grassland. The two catchments are located only 3.5 km from each other (Figure 1a), have a similar elevation range (50–135 m a.s.l for Basper and 33–200 m a.s.l for Manobo) and the same soil type (Eutric Cambisols; clay loam texture) and geology (Gabbro), and are exposed to the same climatic conditions, suggesting that hydrological processes in the two catchments were likely very similar when reforestation in the Manobo catchment started. The Manobo catchment was

reforested after the Manobo tribe was relocated to this area. The choice of which land to reforest was thus based on land tenure and not suitability of the land for reforestation (Zhang, Bruijnzeel, Quiñones, et al., 2019). However, the Basper degraded grassland catchment still experienced landsliding (Zhang et al., 2018), while the landslide scars in the reforested Manobo catchment have been revegetated and stabilized. The sediment load during the pre-Haiyan study period in the Basper grassland catchment was 1.6 t/ha (Zhang et al., 2018). This suggests that during the time that the Manobo forest was established, the Basper catchment underwent continued degradation, erosion, and reductions in soil storage capacity. We refer to Zhang, Bruijnzeel, Quiñones, et al. (2019) for a more detailed justification of the space-for-time approach used here.

The climate is tropical ever wet (Köppen-type Af). Long-term temperature and precipitation data are available for the Tacloban airport (1977–2012 period; PAGASA Office, Tacloban), which is located 8 km from Basper catchment and 11 km from the Manobo catchment. Mean annual precipitation is 2,666 mm/year (range: 1,435–4,790 mm/year). Mean monthly precipitation is greatest in December (378 mm) and January (323 mm) and least in April (127 mm) and May (147 mm). Monthly average temperatures vary between 25.7 °C in January and 28.1 °C in May. This study focuses on the period between 12 June and 7 November 2013 rather than a full year because typhoon Haiyan caused widespread destruction of vegetation in both catchments (Zhang, Bruijnzeel, van Meerveld, et al., 2019) and severe landsliding at Basper on 8 November 2013 (Zhang et al., 2018). Total precipitation during the study period was 1,028 mm in Basper and 1,004 mm in Manobo; average precipitation at Tacloban airport for the June–October period is 950 mm. The 90th percentile of the 5-min precipitation intensity for the June–November 2013 period was 24 mm/hr for Basper and 18 mm/hr for Manobo.

Soils in both catchments are Eutric Cambisols with a clay loam texture that grades into sandy clay loam below 0.9-m depth (Zhang, Bruijnzeel, Quiñones, et al., 2019). Field measurements using a constant-head permeameter suggest large differences in the saturated soil hydraulic conductivity (K_{sat}): the median K_{sat} at 20-cm depth was 2.9 mm/hr for the Basper grassland ($n = 17$) and 59 mm/hr for the Manobo reforest ($n = 18$), with interquartile ranges of 0.8–6.6 mm/hr at Basper and 32–114 mm/hr at Manobo. These differences suggest that surface saturation and overland flow are much more likely to occur at the degraded Basper catchment than at the reforested Manobo catchment, which has likely more interflow or deeper drainage. Further details on the soil characteristics are given in Zhang, Bruijnzeel, Quiñones, et al. (2019).

3. Methods

3.1. Field Measurements

Precipitation was measured at two locations in each catchment using HOBO recording tipping bucket rain gauges (Onset Computer Corporation, USA) connected to HOBO Pendant event data loggers. One gauge was located in an open area near the outlet of each catchment and the other near the ridge (Figures 1b and 1c). Daily precipitation measurements with a 100-cm² manual rain gauge placed next to the lower recording rain gauges were used as a check of the recording gauges. All rain gauges were placed ~1 m above the soil surface. For the analyses we used the average precipitation of the two recording gauges for each catchment. We did not correct precipitation amounts for wind-related catch errors because wind speeds were generally low (median value of 1.2 m/s at the Basper ridge site). Sequential rainfall samplers (Kennedy et al., 1979) installed near the lower rain gauges were used to obtain precipitation samples in 8-mm increments and were generally emptied within 1 or 2 days after an event.

Stream stage was measured behind sharp-crested compound weirs at 5-min intervals using HOBO U20 loggers. The atmospheric pressure was measured in a nearby hut in each catchment using HOBO U20 loggers as well. Volumetric (bucket and stopwatch) and current-meter (Price Type AA current meter) measurements were used to check the validity of the V-notch weir equation for the two weirs. For water levels above the V-notch, the Bergmann compound weir equation (as given in USBR, 1997) was used. The weir was overtopped for 0.12% of the total time (representing 21% of the total flow) at the Basper degraded grassland catchment and for 0.13% of the total time (18% of the total flow) at the Manobo reforested catchment.

The electrical conductivity (EC) of stream water was measured using HOBO U24 loggers installed behind each weir. The data from the loggers were regularly checked against manual EC measurements using a

CyberScan PC300 pH/Conductivity/TDS Meter (ENVC0, Australia). Stream samples were collected using U59 single stage samplers (i.e., bottles with a siphon-shaped air exhaust; Colby, 1961; Schick, 1967) installed at different heights behind the weirs. The full bottles were generally replaced within 1–2 days after an event. Manual grab samples were taken during some events as well.

Soil water samples were collected using ceramic-cup suction lysimeters (initial suction of ~600 hPa) installed at 20 and 55 cm below the soil surface at a footslope and middle- and upper-slope location in the Basper grassland catchment and at a lower- and middle-slope location at the Manobo reforested catchment. The sample closest to an event was used to represent the soil water composition during the event. Groundwater samples were taken from piezometers (91–265 cm deep) installed at the same locations as the suction lysimeters in both catchments (see Figures 1b and 1c). However, for most events groundwater samples were only available for the footslope piezometers (91-cm depth in Basper and 120-cm depth in Manobo). All water samples were filtered at Visayas State University using 0.45- μ m Millipore filters. The samples were analyzed for stable water isotopes (^{18}O and ^2H) using laser spectroscopy at the Global Institute for Water Security at the University of Saskatchewan, Canada, and are reported using the delta notation relative to Vienna Standard Mean Ocean Water. The samples were analyzed for base chemistry using Inductively Coupled Plasma Optical Emission Spectrometry at the WaterLab of the VU University Amsterdam, The Netherlands.

3.2. Data Analyses

3.2.1. Streamflow Characteristics During the Study Period

To provide an unbiased comparison of streamflow for the two study catchments, the analyses were restricted to periods when streamflow was recorded at both sites, which was 85% of the study period from 12 June to 7 November 2013 (i.e., 127 days out of the 149-day period). Total precipitation during the days included in the analyses was 915 mm for Basper and 842 mm for Manobo, representing 89% and 84% of the respective precipitation totals for the entire study period. For the matching time periods, we calculated several streamflow characteristics that describe the magnitude of the streamflow, such as the total amount of streamflow, the mean, and median streamflow, as well as the variability in streamflow, such as the flood pulse counts (i.e., the number of times that streamflow exceeded the median flow by a factor of 3 or the 75th percentile of flow), the Richard-Baker Flashiness index (Baker et al., 2004), and the percentage of time on the rising limb. To describe the drainage of the catchments, we determined the slope of the flow duration curve between the 33rd and 66th percentiles of flow (Olden & Poff, 2003) and constructed the master recession curve using the matching strip technique (Nathan & McMahon, 1990; Snyder, 1939). All streamflow characteristics were based on 5-min data, except for the flood pulse counts, the number of substantial streamflow increases, the Richard-Baker flashiness index, the percentage of time on the rising limb, and the master recession analysis, which were based on hourly averaged data to minimize the effect of noise in the 5-min data.

3.2.2. Event Characteristics

Streamflow response characteristics were computed for the precipitation events for which there were data for both catchments. All events larger than 5 mm that were preceded by at least 6 hr without precipitation and that resulted in a clear storm hydrograph were included in the analyses. To determine the amount of stormflow for each event, the straight line separation method was used (Hewlett & Hibbert, 1967). The start of the event was defined as the first time step that streamflow increased after the start of precipitation, while the end of the event was defined as the time that stormflow ended based on the straight line separation or the start of the next event. If an event was followed by another event within 6 hr, the next event was only counted as a separate event if stormflow was less than 5% of the total flow at the start of the successive event. Otherwise, the two events were analyzed together. These event selection criteria resulted in 40 events for the Basper grassland catchment and 35 events for the Manobo reforested catchment.

For each event, the 5-min precipitation and streamflow data were used to determine several event characteristics, such as the total amount of stormflow, the stormflow runoff ratio, the lag time between peak precipitation intensity and peak streamflow (peak lag time), and the lag time between the centroids of precipitation and stormflow (centroid lag time). The storm runoff ratio was determined by dividing the total event stormflow amount by the event total precipitation. The Mann-Whitney U test was used to determine if the differences in the median event characteristics for the two study catchments were statistically significant (confidence level of 0.05).

3.2.3. Isotope-Based Hydrograph Separation and Mixing Plots

We used isotope-based hydrograph separation for two events for which a sufficient number of isotope samples were available for precipitation and streamflow for both catchments and the isotopic composition of the precipitation differed from the pre-event streamflow composition. The fraction of event water for each time step was determined, according to

$$f_e = \frac{C_s - C_p}{C_e - C_p}, \quad (1)$$

where f_e is the fraction of event water in streamflow, C_s is the concentration (here $\delta^2\text{H}$ or EC) in streamflow, C_e is the concentration of the event water, and C_p is the concentration of the sample taken prior to the event, which was assumed to represent the pre-event water composition. We used the incremental weighted mean concentration of the precipitation (McDonnell, 1990) to characterize the event water composition C_e . The uncertainty in the fraction of pre-event water was calculated following the method of Genereux (1998), assuming an uncertainty in the $\delta^2\text{H}$ of the streamflow samples of 1‰ and an uncertainty in pre-event water $\delta^2\text{H}$ of 2‰. We determined the maximum event water contribution for each event based on the sample for which the maximum event water fraction was calculated. We linearly interpolated the event water fractions for the different sampling times and multiplied these values by the streamflow to obtain the event water contributions at 5-min intervals during the event. The average event water contribution to streamflow was calculated as the ratio of the sum of event water and the event total streamflow. In addition, we calculated the fraction of precipitation that directly contributed to streamflow as the ratio of the sum of event water and event total precipitation (cf. von Freyberg et al., 2018).

The two events for which the isotope data allowed isotope-based hydrograph separations were the event of 27 July 2013 (bringing ~50 mm of precipitation to both catchments) and tropical storm Rumbia (locally known as tropical storm Gorio, delivering ~150–175 mm of precipitation on 28–29 June 2013). The latter event was the largest event during the study period. Between 1976 and 2011, there were 21 events at Tacloban airport with more than 150 mm of precipitation in 1 day (daily precipitation was larger than 160 mm for only 10 days). We used the chemical data for the two events and for the ~45-mm event on 21 June 2013 (for which good isotope data for precipitation were not available) for three-component hydrograph separation (Hooper et al., 1990), to determine the relative contributions of groundwater, soil water, and precipitation to streamflow during these events.

We also analyzed the changes in stream water EC during rainfall events to obtain estimates of the maximum event water contribution to streamflow during almost all events during the study period (EC data were not available for two events [out of 40] in Basper and one event [out of 35] in Manobo). Because rainfall EC data were not available for each individual event, an average EC of 8 $\mu\text{S}/\text{cm}$ was used in the computations for all events (range: 3–20 $\mu\text{S}/\text{cm}$; EC < 10 $\mu\text{S}/\text{cm}$ for 16 out of 18 samples). Several recent studies have shown that, despite not being a conservative tracer, EC can be useful for hydrograph separation (Inserillo et al., 2017; Pellerin et al., 2008; Robinson et al., 2008). However, other studies have shown that there can be substantial differences between EC- and isotope-based hydrograph separation results for some events (Litt et al., 2015; Penna et al., 2015). For example, Laudon and Slaymaker (1997) showed that event average event water contributions to streamflow were 10–20% higher when EC was used for the calculations than for the isotope- or silica-based calculations. However, other studies found that the use of EC data led to an underestimation of the event water contributions (Blume et al., 2008; Vidon & Cuadra, 2010). Penna et al. (2015) showed that differences in the EC- and isotope-based event water fractions varied seasonally and were small (<10%) for small to medium sized (<20 mm) events but the difference was 21% for a 66-mm event. Thus, the EC-based hydrograph separation results need to be interpreted with caution if the differences are small.

4. Results

4.1. Streamflow Responses

Even though total precipitation during the study period was 8% higher for the Basper degraded grassland catchment than for the Manobo reforested catchment (Table 1) and the 95th percentile of the precipitation intensity was higher for the Basper catchment than the Manobo catchment, there were no statistically

Table 1

Streamflow Characteristics for the Basper Degraded Grassland Catchment and the Manobo Reforested Catchment for the 127 days (Out of the 149) Between 12 June and 7 November 2013 for Which Streamflow Data Were Available for Both Catchments

Streamflow characteristic	Basper degraded grassland	Manobo reforest
Total precipitation (mm)	915	842
<i>Magnitude</i>		
Total streamflow (mm)	391	244
Runoff coefficient (%)	43	29
Mean flow (mm/hr)	0.13	0.08
Median flow (mm/hr)	0.05	0.01
<i>Variability</i>		
Ratio of mean and median flow (–)	2.8	7.2
Coefficient of variation (–)	5.6	6.0
Ratio of the difference between the 75th and 25th percentiles of flow and the median flow (–)	1.86	2.99
Flood pulse count (>75th percentile; –)	36	17
Flood pulse count (>3× median flow; –)	37	21
Number of substantial streamflow increases (>10% and 0.1 mm/hr [with more than 2 hr of no increase prior to the rise]; –)	32	10
Percentage of time on fast rising limb (fraction of time that flow was higher than in the previous hour by at least 10% and 0.1 mm/hr; %)	1.6	0.6
R-B flashiness index	0.47	0.16
Slope of the flow duration curve between the 66th and 33rd percentiles (–)	0.18	0.05

significant differences in median event size or event average precipitation intensity for the two catchments (Table 2).

Streamflow responses for the Basper and Manobo catchments were very different (Figure 2). Streamflow at the Basper degraded grassland catchment was much more variable and responded to almost every precipitation event, whereas streamflow at the Manobo reforested catchment only responded considerably to the largest events (Figure 2). This is reflected in the higher flood pulse counts, larger number of flow increases, higher flashiness index, and larger percentage of time on the rising limb for the Basper grassland catchment compared to the reforested Manobo catchment (Table 1). The cumulative streamflow versus cumulative precipitation curves were also very different for the two catchments (Figure 3). For the Basper grassland catchment, cumulative streamflow increased almost linearly with cumulative precipitation, while the curve for the Manobo reforested catchment was much more step like, reflecting the more delayed response to precipitation (e.g., the large increase in cumulative streamflow after the major increase in precipitation during tropical storm Rumbia in late June) and the many precipitation events that did not result in a substantial streamflow response (e.g., the flat part of the curve for the month of July, for which the runoff ratio was 16% compared to 47% for the Basper grassland catchment but note that the total precipitation in July was also less for the Manobo reforested catchment (153 mm vs. 232 mm for Basper).

Event stormflow amount increased with event total precipitation for both catchments (Figure 4). There appears to be a threshold at ~10 mm of precipitation for both catchments, but due to a lack of data for small events and the big influence of tropical storm Rumbia, it was difficult to define the threshold exactly. The slope of the relation between event total stormflow and precipitation for events below the threshold was much larger for the Basper catchment than the Manobo catchment (0.054 vs. 0.006), but the correlation was very low ($r^2 < 0.1$) and not significant. The corresponding slopes after the threshold also differed between the two catchments when excluding the largest event (0.41 and 0.20 for Basper and Manobo, respectively) but were similar when including the tropical storm (0.51 and 0.48, respectively; Figure 4). Similar to the overall runoff ratios for the study period (Table 1), the median event-based runoff ratio was much larger for the Basper grassland catchment than for the Manobo reforested catchment (Table 2).

Peak flows, as well as mean and median flows, were also much higher for the Basper grassland than for the Manobo reforested catchment (Table 1 and Figure 5). Even though the correlations between event size or

Table 2

The Median (and Mean; top row) and Range (Min-Max; Second Row) of the Event Characteristics for the Basper Degraded Grassland ($n = 40$) and Manobo Reforested ($n = 35$) Catchments, As Well As the Mann-Whitney Ranked Sum Test p Values, and the Relative frequency Distribution of the Event Water Characteristics, where the Box Represents the 25th and 75th Percentiles, the Solid Line the Median, the Dashed Line the Mean, the Whiskers the 10th and 90th Percentiles and the Dots the Outliers (Basper: Upper Box Plot in Orange, Manobo: Lower Box Plot in Green)

Event characteristic	Basper degraded grassland	Manobo reforest	p value	Relative frequency distribution
Event size (mm)	11.6 (18.6) 4.1–154	11.3 (18.5) 5.3–174	0.996	
Maximum precipitation intensity ($\text{mm } 5 \text{ min}^{-1}$)	3.6 (3.9) 0.5–8.4	2.7 (3.3) 0.5–6.3	0.222	
Total stormflow (mm^a)	1.7 (5.0) 0.01–76	0.09 (3.5) 0.002–80	0.006	
Runoff ratio (%)	12.5 (15.0) 0.17–50	0.5 (6.8) 0.04–46	<0.001	
Peak streamflow ($\text{mm } 5 \text{ min}^{-1}$)	0.20 (0.53) 0.0009–2.13	0.01 (0.06) 0.0007–1.18	<0.001	
Lag time between peak precipitation intensity and peak streamflow (min)	10 (11) 0–60	20 (39) 0–270	0.001	
Lag time between centroid of precipitation and centroid of stormflow (min)	25 (34) 5–90	50 (130) 10–485	0.006	
Change in EC during the event ($\mu\text{S}/\text{cm}^b$)	187 (162) 20–282	51 (77) 11–199	<0.001	

Note. EC = electrical conductivity.

^aBased on the straight line hydrograph separation method. ^b $n = 38$ for Basper and 34 for Manobo.

maximum precipitation intensity and peak flow were poor and not significant for both catchments, peak flow rates were more affected by peak precipitation intensities for the Basper grassland catchment than for the Manobo reforest (Figure 5). Streamflow responses were not only larger for the Basper catchment but were also significantly faster. The median lag time between peak precipitation intensity and peak streamflow was only ~10 min for the Basper grassland catchment and significantly shorter than for the Manobo reforested catchment (20 min; but note the large uncertainty because the data were recorded at 5-min intervals; Table 2). The difference in median lag times between the centroids of precipitation and stormflow was also a factor of 2, although the differences in the average centroid lag times were much

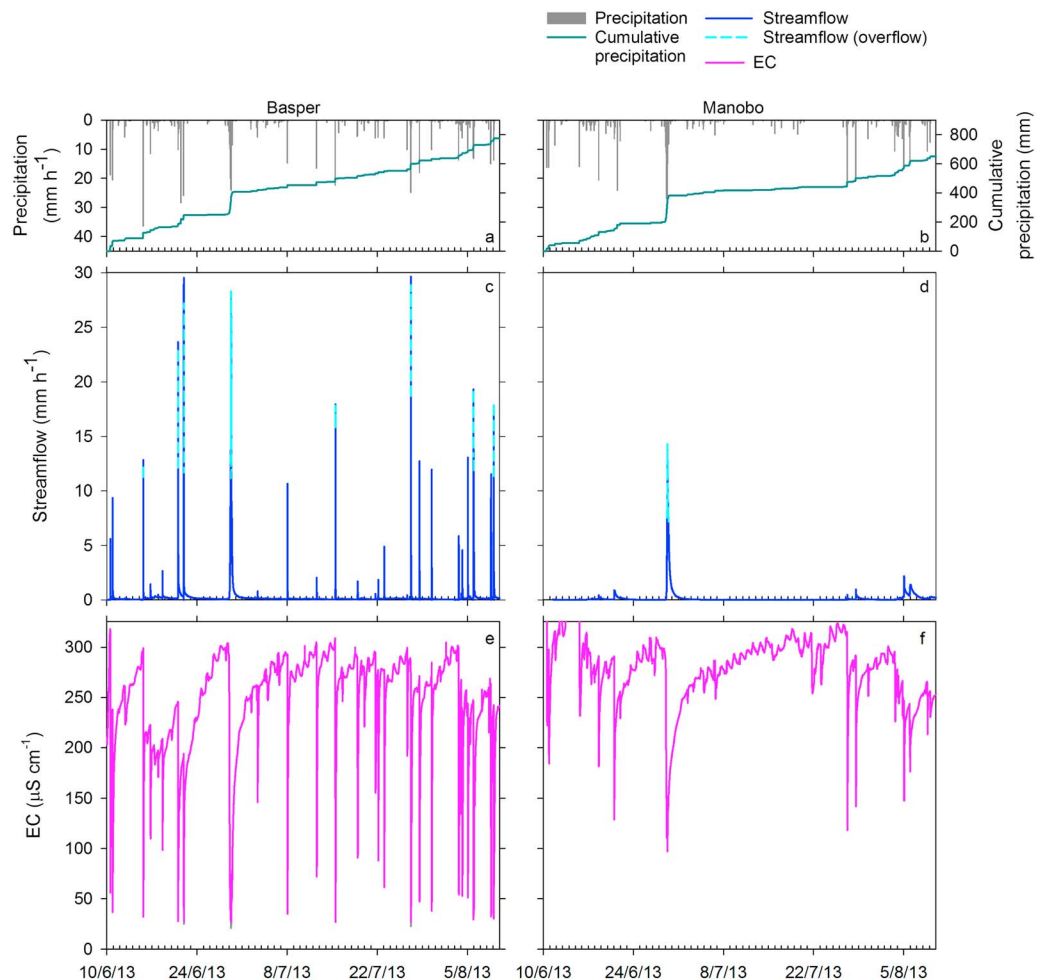


Figure 2. Time series of hourly and cumulative precipitation (a, b), 5-min streamflow (c, d), and electrical conductivity (EC) of stream water (e, f) for the Basper degraded grassland catchment (a, c, e; left) and the Manobo reforested catchment (b, d, f; right) for the period between 10 June and 10 August 2013. The streamflow when the V-notch of the weir overflowed is indicated by the light blue line.

larger (23 min for Basper vs. 130 min for Manobo; Table 2). The master recession curve was steeper for the Basper grassland catchment than the Manobo reforested catchment for the first 2 days and vice versa afterward (Figure S1 in the supporting information), suggesting that low flows decreased faster in the reforested catchment than in the grassland catchment.

4.2. Isotope-Based Hydrograph Separations and Mixing Diagrams

The streamflow responses to the event on 27 July 2013 (~50 mm of precipitation) were very different for the two catchments (Figure 6). Streamflow in the Basper grassland increased from $0.004 \text{ mm } 5\text{-min}^{-1}$ to $2 \text{ mm } 5\text{-min}^{-1}$ within 75 min. The peak lag time was only 15 min, and the centroid lag time was 10 min. Streamflow in the Manobo reforested catchment changed from a low $0.0003 \text{ mm } 5\text{-min}^{-1}$ to $0.039 \text{ mm } 5\text{-min}^{-1}$; peak and centroid lag times were 10 min and 3 hr 35 min, respectively. Storm flow runoff ratios for this event were 36% at Basper and 3% at Manobo. The isotope-based hydrograph separation result for this event suggests an average event water contribution to streamflow (i.e., the ratio of the total amount of event water to total streamflow) of 81% ($\pm 8\%$) for Basper and 35% ($\pm 13\%$) for Manobo. The corresponding fraction of precipitation that directly contributed to streamflow (i.e., the ratio of the total amount of event water and total precipitation) was 29% for Basper and 1% for the Manobo. The maximum event water contributions during the event were 97% ($\pm 22\%$) and 80% ($\pm 12\%$) for the Basper grassland and Manobo reforested catchments, respectively. However, these results are somewhat uncertain, particularly for the Basper catchment because of the lack of samples during peak flow conditions and the rapidly changing isotopic composition of

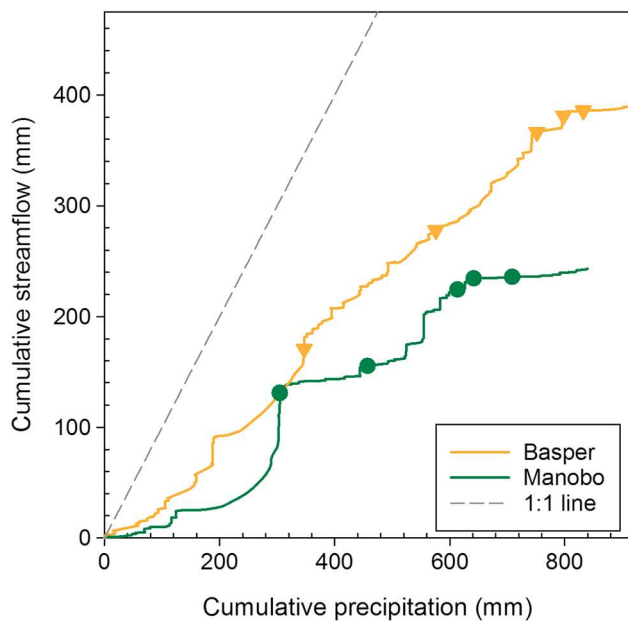


Figure 3. Relation between cumulative streamflow and cumulative precipitation for the days with data for the Basper degraded grassland catchment and the Manobo reforested catchments. The symbols indicate the values on the first of July, August, September, October, and November 2013.

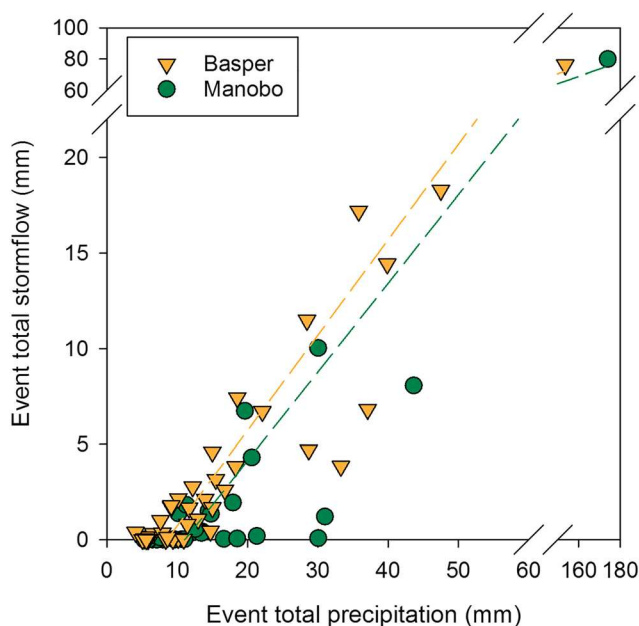


Figure 4. Event total stormflow as a function of event total precipitation for the Basper degraded grassland (orange triangles) and Manobo reforested (green circles) catchments. The stormflow amount was based on the straight line hydrograph separation method. The lines represent the best fitted regression lines ($r^2 = 0.96$ and 0.95 for the Basper and Manobo catchment, respectively). Note the break in the axes in order to be able to show all events in the same graph.

precipitation and streamflow. Furthermore, one sample on the rising limb was isotopically more depleted than any of the precipitation samples until that time and was excluded from the calculations.

During tropical storm Rumbia on 28–29 June 2013, streamflow increased drastically in both catchments (Figure 7). The peak flow rates were different for the two catchments ($2.1 \text{ mm } 5\text{-min}^{-1}$ for Basper vs. $1.2 \text{ mm } 5\text{-min}^{-1}$ for Manobo but note that the V-notch weir was overtopped and peak flow rates are thus more uncertain [because of the lack of discharge measurements at high flow rates]). Streamflow peaked within 5 min of the peak precipitation intensity for both catchments. The centroid lag time was shorter for the Basper grassland catchment than the Manobo reforested catchment (1 hr 25 min vs. 2 hr 40 min). However, the storm runoff ratios were comparable at $\sim 49\%$ and $\sim 46\%$ for the Basper and Manobo catchments, respectively, also in view of the uncertain high flows and possible undercatch of precipitation during periods of intense precipitation and high wind speeds. The average contributions of event water to total streamflow during this event were different: $47\% (\pm 19\%)$ at Basper versus $23\% (\pm 7\%)$ at Manobo. The fraction of precipitation that directly contributed to streamflow was 23% for the Basper grassland catchment and 11% for the Manobo reforested catchment. The maximum event water contributions during the event were $76\% (\pm 12\%)$ for Basper and $42\% (\pm 10\%)$ for Manobo.

Changes in the concentrations of silica, calcium, magnesium, and most other ions during these two events were very similar to the changes in EC (see Figures 6c and 6d and 7c and 7d for the time series for calcium and silica). Soil water concentrations were highly variable, but the mixing plots clearly indicate that stream water was a mixture of groundwater and precipitation and some soil water in both catchments. However, the influence of precipitation was reflected more in the chemistry of the streamflow at the Basper grassland catchment than at the Manobo reforested catchment (Figure 8). The mixing diagrams for the event on 21 June 2013 were similar to those for the other events (Figures 8a and 8b). Three-component hydrograph separation calculations were not possible for all samples collected during the events but do suggest that the relative contribution of groundwater to streamflow decreased during the events and the relative contributions of precipitation increased. The relative contributions of soil water remained relatively stable during the events (varying between 10% and 26% for Basper and between 12% and 30% for Manobo). Three-component hydrograph separation was not possible for any of the peak flow samples from the Basper grassland catchment (leading to unphysical contributions of precipitation $>100\%$ and groundwater contributions $<0\%$). For the Manobo reforested catchment, the maximum precipitation contributions to streamflow were 74% for the 21 June 2013 event and 80% for the 27 July 2013 event. Calculations for tropical storm Rumbia led to unphysical contributions for groundwater (-2.5% and -2.7%) for the two samples collected just before peak flow (the corresponding precipitation contributions to streamflow for these two samples were 74% and 77%). The maximum calculated contribution of precipitation to streamflow for the other samples collected during this large event was 79%.

4.3. EC-Based Hydrograph Separations

The EC of stream water decreased much more and during more events at the Basper grassland catchment than at the Manobo reforested catchment

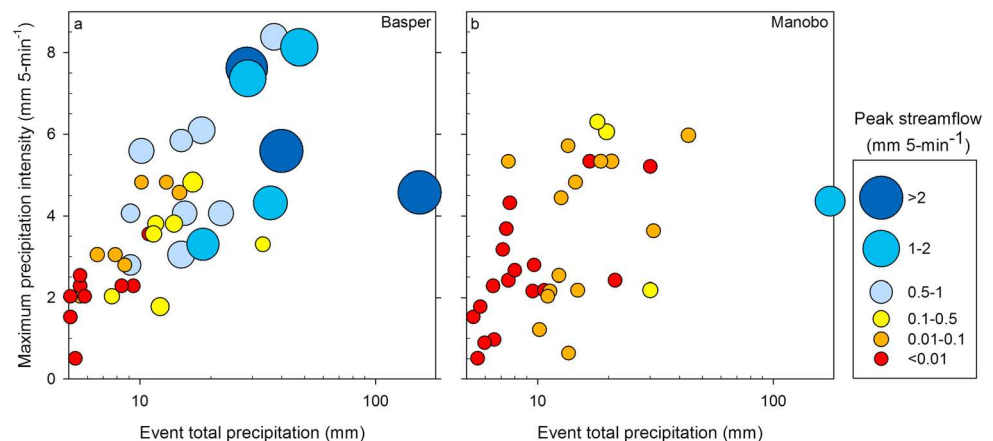


Figure 5. Relation between event total precipitation, 5-min peak precipitation intensity, and peak flow rate for the Basper degraded grassland (a) and the Manobo reforested (b) catchments. Note the log scale in order to be able to show the results for the smaller events better. The figure with a linear scale can be found in Figure S2 in the supporting information.

(Figures 2e and 2f). There was a significant difference in the median change in stream water EC during an event at the two study catchments (median change of 187 $\mu\text{S}/\text{cm}$ for 38 events in the Basper grassland catchment vs. 51 $\mu\text{S}/\text{cm}$ for the 34 events in the Manobo reforestation catchment; Figure 9 and Table 2). The inferred EC-based maximum event water fractions of streamflow were very different as well: median of 74% for Basper compared to 19% for Manobo (Figure S4a in the supporting information).

The EC-based maximum event water fraction during an event increased rapidly with increasing event size for both catchments, but the change for events between 6 and 12 mm of precipitation was much larger for the Basper grassland catchment than for the Manobo reforested catchment (Figure 10a). Similarly, the EC-based maximum event water fraction increased rapidly with event maximum precipitation intensity at Basper for maximum precipitation intensities larger than 2.0 $\text{mm } 5 \text{ min}^{-1}$, whereas at Manobo it did not change much until a maximum intensity of 3.5 $\text{mm } 5 \text{ min}^{-1}$ (Figure 10b). The EC-based maximum event water contributions to streamflow increased with increasing antecedent streamflow for the Basper catchment ($r^2 = 0.51$ for an exponential rise to a maximum), but there was no such relation for the Manobo catchment (Figure S4b in the supporting information).

5. Discussion

5.1. Runoff Generation Mechanisms in the *Imperata* Grassland and Reforestation Catchments

The runoff responses were very different for the two catchments, indicating considerable differences in the runoff generation mechanisms. The storm runoff ratios for events smaller than ~ 10 mm were about 5% for the Basper degraded grassland catchment and 0.6% for the Manobo reforested catchment. This suggests that for these small events, most of the precipitation was stored in the soils and only a small fraction of the catchment contributed to streamflow. Interception losses were also considerable for these small events and were larger for the Manobo reforested catchment than the Basper grassland catchment (Zhang, Bruijnzeel, van Meerveld, et al., 2019). The minimum contributing areas (Dickinson & Whiteley, 1970) included the stream channel, near-stream zones, and landslide slip surfaces for the Basper grassland catchment but only the channel network (and perhaps a small fraction of the riparian zone) for the Manobo reforested catchment. Average runoff ratios for 10–140 mm events were 41% and 20% for the Basper grassland and Manobo reforested catchment ($\sim 25\%$ for Manobo when using throughfall instead of gross precipitation), suggesting contributions from much larger fractions of the grassland catchment than for the reforested catchment for all events, except tropical storm Rumbia. The extremely rapid responses, the large changes in stream chemistry, and the large event water contributions for the Basper catchment all suggest that overland flow dominated streamflow in the grassland catchment for most events. The very low surface and near-surface soil hydraulic conductivities (Zhang, Bruijnzeel, Quiñones, et al., 2019), along with shallow groundwater observations (Zhang et al., 2018), suggest that widespread infiltration excess overland flow is the dominant runoff mechanism in the Basper grassland catchment, in addition to saturation overland flow on some parts of

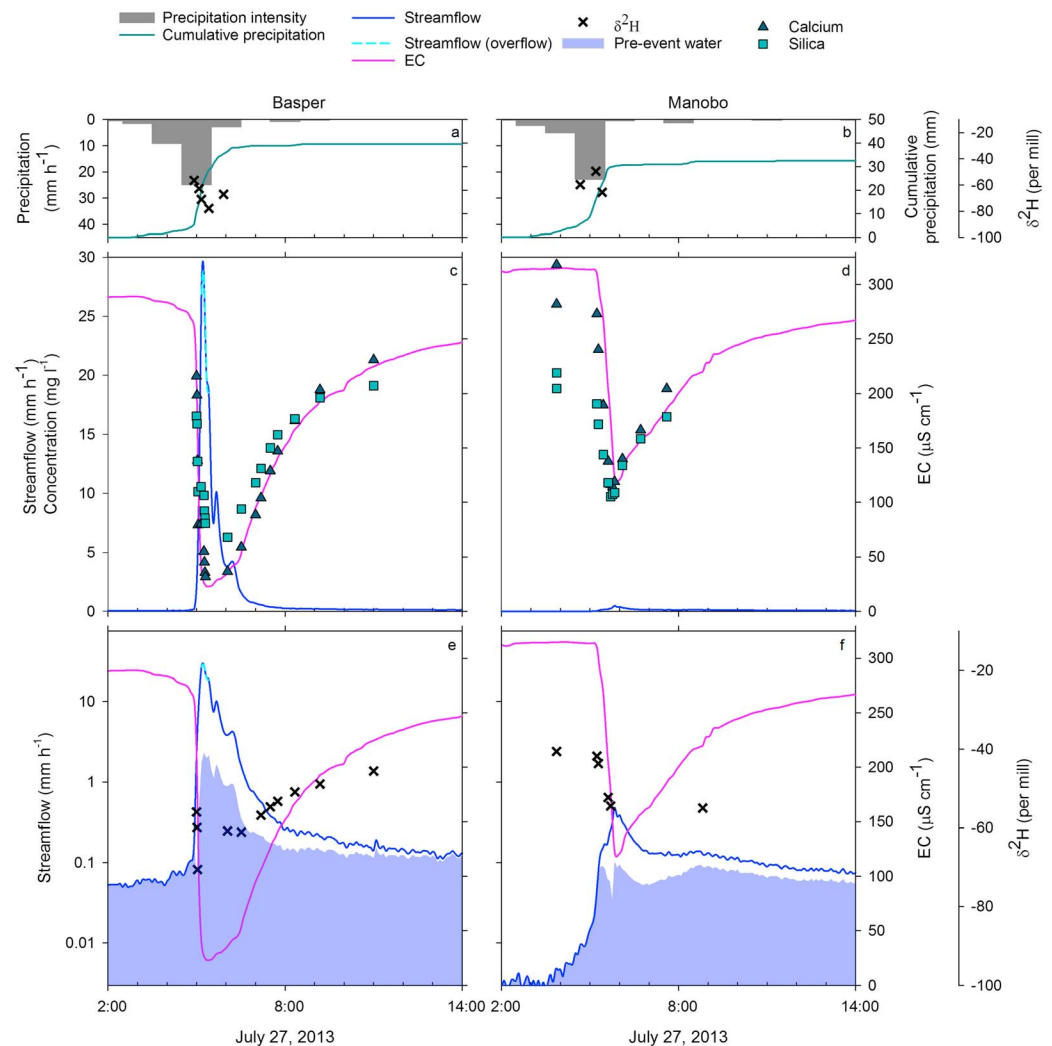


Figure 6. Hourly and cumulative precipitation and the isotopic composition of precipitation (deuterium; a, b), 5-min streamflow and Electrical Conductivity (EC) data and silica and calcium concentrations (c, d), and isotopic composition (deuterium) of stream water and the deuterium-based pre-event water contribution to streamflow (e, f) during the 27 July 2013 event for the Basper degraded grassland (left; a, c, e) and Manobo reforested (right; b, d, f) catchments. The streamflow when the V-notch of the weir overflowed is indicated by the light blue line. Figures 6c and 6d show streamflow on a linear scale, while Figures 6e and 6f show streamflow on a log scale in order to better show the streamflow response at the Manobo reforested catchment.

the hillslope. The rapid changes in stream stage and EC observed for almost all events (Figure 2) further suggest that overland flow was generated during almost all events in the grassland catchment. Conversely, in the reforested Manobo catchment, only large events led to substantial changes in streamflow and EC (Figure 2). Streamflow at Manobo barely responded to the 50-mm event on 27 July 2013. The very low storm runoff ratio (3%) and event water to total precipitation ratio (1%) suggest that a large portion of the event water during this event was generated from precipitation falling on the channel.

The runoff ratios for the largest event (tropical storm Rumbia) were almost similar for the two catchments (given the uncertainties in the precipitation and streamflow measurements for this extreme event), but the differences in the timing of the response, the magnitude of peak streamflow, and the isotope-based event water contributions to streamflow suggest that runoff processes were still different. Overland flow was likely still dominant at the Basper grassland catchment. The low saturated hydraulic conductivity at 60-cm depth (Zhang, Bruijnzeel, Quiñones, et al., 2019) and the relatively long centroid lag time suggest that lateral flow was likely the dominant runoff generation mechanism at the Manobo reforested catchment. Groundwater

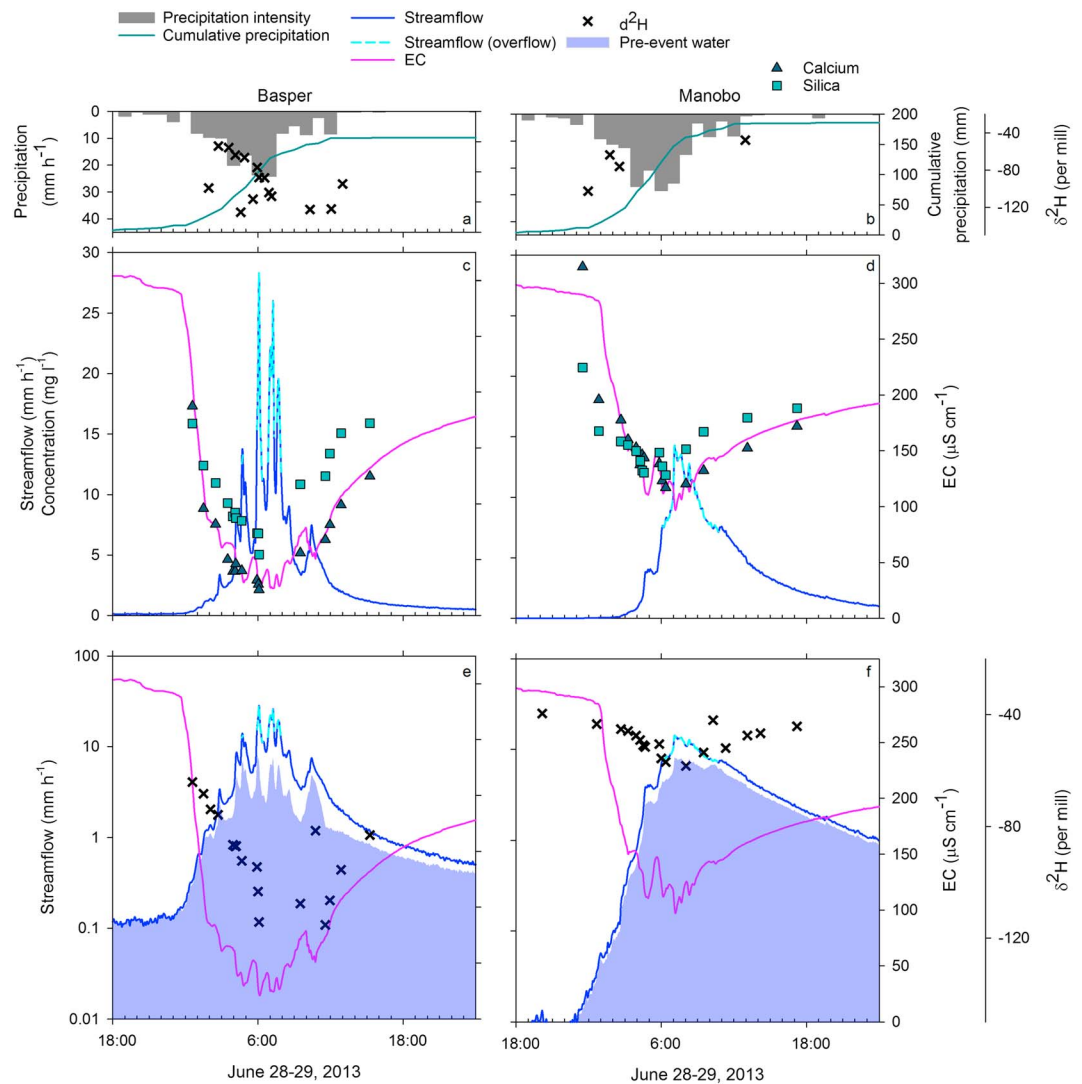


Figure 7. Hourly and cumulative precipitation and the isotopic composition of precipitation (deuterium; a, b), 5-min streamflow and Electrical Conductivity (EC) data and silica and calcium concentrations (c, d), and isotopic composition (deuterium) of stream water and the deuterium-based pre-event water contribution to streamflow (e, f) during the 28–29 June 2013 event (tropical storm Rumbia) for the Basper degraded grassland (left; a, c, e) and Manobo reforested (right; b, d, f) catchments. The streamflow when the V-notch of the weir overflow is indicated by the light blue line. Figures 7c and 7d show streamflow on a linear scale, while Figures 7e and 7f show streamflow on a log scale.

levels rose to 30 cm below the surface at the footslope in Manobo, thereby likely activating lateral macropores flow (cf. Noguchi et al., 1997; Robinet et al., 2018; Schellekens et al., 2004). Chandler and Bisogni (1999) found that pipe flow contributed most of the interflow at a forest site on epikarst in the Philippines. No macropore flow samples were collected during this event, but a sample of concentrated seepage in the streambank during the 27 July event had the same chemical signature as streamflow (i.e., a mixture of groundwater and throughfall).

5.2. Effect of Reforestation on Runoff Generation Mechanisms

The comparative results of the space-for-time substitution approach suggest that reforestation of the Manobo catchment has drastically improved soil hydraulic properties, thereby considerably reducing the amounts of overland flow, so that the streamflow increases during precipitation events at Manobo are now much smaller, more delayed, and are only substantial during large events (Figure 2 and Table 1). Streamflow at the Manobo reforested catchment is still a mixture of groundwater and precipitation (throughfall) but the fraction of precipitation is now much smaller (Figures 6–8). The results, therefore,

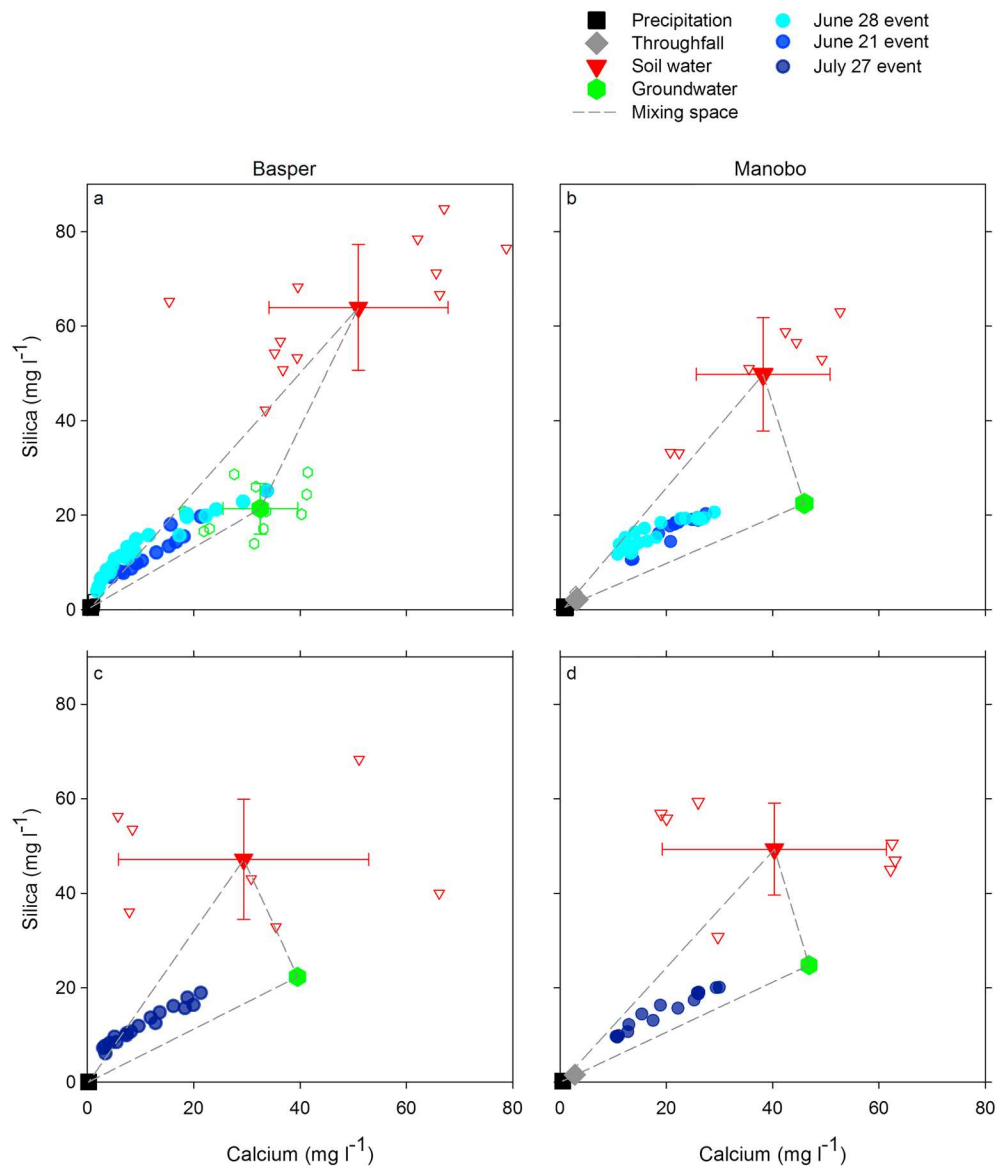


Figure 8. Mixing diagrams for the events on 21 and 27–28 June 2013 (top row; a, b) and 27 July 2013 (bottom row; c, d) for the Basper degraded grassland (left column; a, c) and the Manobo reforested (right column; b, d) catchments. The individual precipitation, throughfall (Manobo only), groundwater, and soil water samples are indicated by open symbols. The filled symbol indicates the average; the error bars indicate the standard deviation of all precipitation, throughfall, soil water, and groundwater samples when more than one sample was available. The streamflow samples are indicated by the blue circles.

suggest that reforestation can change streamflow dynamics and the dominant flow pathways for the better, provided that the forest and soil are allowed to develop uninterrupted over a sufficiently long period (cf. Ghimire et al., 2014). García-Ruiz et al. (2008) reported a similar difference in runoff response for catchments in the Pyrenees, where a highly degraded catchment responded to all rainfall events and a forested catchment only to large events in the wet period. Zhou et al. (2002) and Krishnaswamy et al. (2012) similarly showed major reductions in the storm runoff response after reforesting bare land in South China and overgrazed degraded forest land in India, respectively. The results are also in agreement with previous hydrochemical studies (Chaves et al., 2008; Robinet et al., 2018) and runoff plot studies (Chandler & Walter, 1998) that suggested that overland flow was more widespread in grazed pastures or pasture fallows than in (re)forested sites. In addition to the much higher infiltration rates in the reforested Manobo catchment than the degraded Basper catchment and resulting decreases in overland flow, the soil

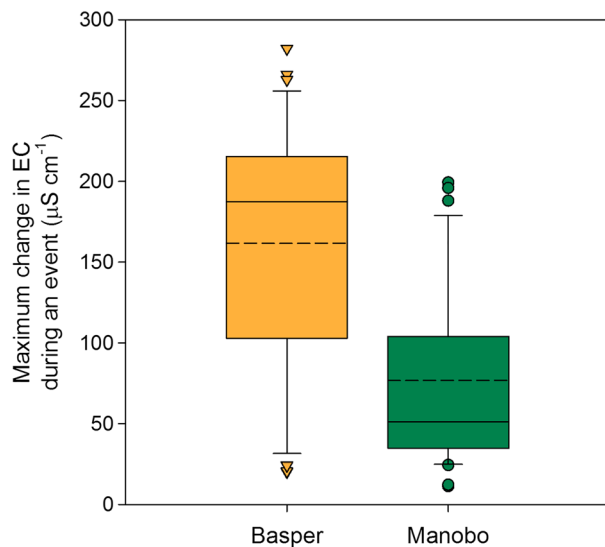


Figure 9. Box plots of the maximum change in Electrical Conductivity (EC) during an event for the Basper degraded grassland ($n = 38$) and the Manobo reforested catchment ($n = 34$). The box represents the interquartile range, the solid line the median, the dashed line the mean, the whiskers the 10th and 90th percentiles, and the symbols the outliers. The differences in the median values are statistically significant ($p < 0.001$).

storage capacity of the Basper grassland has likely been diminished by the continued soil erosion and landsliding (cf. Chandler, 2006).

The difference in area between the two catchments is unlikely to account for the large observed differences in the streamflow responses. Neither catchment has a large riparian zone; both have steep hillslopes. The Basper catchment has more gullies and the mapped drainage density is higher (Figure 1), reflecting both the prevailing higher erosion rates (Zhang et al., 2018) and a greater visibility of gullies and streams on aerial photographs in the absence of trees. While routing will be shorter in the smaller Basper grassland catchment, this cannot explain the observed differences in runoff ratios and event water contributions to streamflow during the small- and middle-sized events. Furthermore, both catchments are very small so that routing is very fast. Both catchments are also much bigger than the runoff plots for which the scale effect on overland flow is often large. Furthermore, research in drylands has shown that the effect of plot size on overland flow is smallest for the most degraded sites (Moreno-de las Heras et al., 2010). The literature on the effect of catchment size on event water contributions is unclear (Klaus & McDonnell, 2013). Litt et al. (2015) explained the lower event water fractions for a pasture catchment compared to forest in Panama by the smaller size of the pasture catchment (but the differences in hydrometric responses were much larger than those based on geochemical and isotope tracers). If this would be the case for the study catchments, this would mean that the dif-

ference in event water fractions would be even larger if the Basper and Manobo catchments were the same size.

The differences in the centroid lag time, isotope-based event water contributions to streamflow, and peak flow rates for the two catchments during tropical storm Rumbia on 28–29 June 2013 (Figure 7) suggest that differences in runoff generation processes and responses persist, even for the largest events. This is different to the results for most paired catchment studies where soils were not degraded (e.g., Hewlett, 1982; Hsia, 1987; Iroumé et al., 2006) but is in line with results obtained for badland and reforested catchments in the Pyrenees (Lana-Renault et al., 2014) and Southeast France (Mathys et al., 1996). The difference in runoff generation mechanisms between the catchments must also have a large effect on peak flows and water

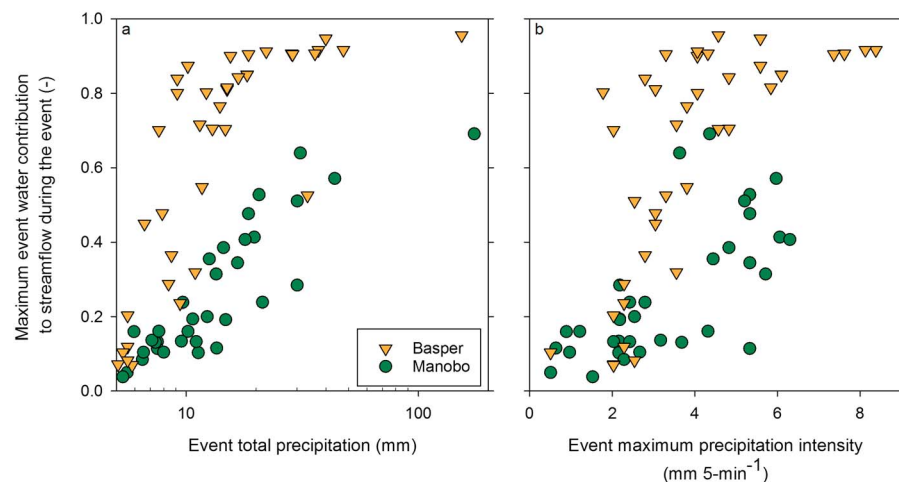


Figure 10. Maximum event water contribution during an event based on the electrical conductivity data as a function of event total precipitation (a) and the maximum 5-min precipitation intensity (b) for the Basper degraded grassland (orange triangles) and Manobo reforested (green circles) catchments. Note that the electrical conductivity-based maximum event water contributions can differ substantially from the isotope-based event water contributions (see section 5.3 and Table 3).

Table 3

The Average and Maximum Event Water Contributions to Streamflow (%) for the 50-mm 27 July 2013 Event and the 150- to 175-mm 28–29 June 2013 Event for the Basper Degraded Grassland and the Manobo Reforested Catchments

Event		Basper degraded grassland		Manobo reforest		
		$\delta^2\text{H}$	EC	$\delta^2\text{H}$	EC (P)	EC (TF)
27 July 2013	Average	81 ± 8	81	35 ± 13	27	31
	Maximum	97 ± 22	95	80 ± 12	64	75
28–29 June 2013	Average	47 ± 19	76	23 ± 7	50	59
	Maximum	76 ± 12	96	42 ± 10	59	82

Note. The EC-based hydrograph separation results for Manobo are shown when using the EC of precipitation (P; EC = 8 $\mu\text{S}/\text{cm}$) and when using the EC of throughfall (TF; average EC = 52 $\mu\text{S}/\text{cm}$; $n = 6$). For the time series of the $\delta^2\text{H}$ - and EC-based event water contributions, see Figure S3 in the supporting information. EC = electrical conductivity.

quality for even larger events. The streamflow response at Manobo during typhoon Haiyan (228 mm of precipitation within several hours on 8 November 2013) was not very different from that during tropical storm Rumbia, but streamflow at Basper was very much larger and the weir became completely buried by landslide sediment (Zhang et al., 2018). Such observations corroborate the contention that the runoff generation mechanisms at the two sites also differ for even larger events than those reported here.

5.3. Effect of Event Size and Intensity on EC-Based Event Water Contributions to Streamflow

Even though EC is not a conservative tracer, there was a very good correspondence between the isotope- and EC-based hydrograph separation results for the mid-sized 27 July event (Table 3 and Figure S3 in the supporting information). This suggests that for this mid-sized event the influence of the nonconservative behaviour of EC was relatively small compared to the large differences in the maximum event water contributions for the two catchments. However, the differences between the EC- and isotope-based hydrograph separation results were larger for tropical storm Rumbia for which the EC-based hydrograph separation results led to higher average and maximum event water contributions than the isotope-based hydrograph separation results (Table 3 and Figure S3 in the supporting information). This suggests that the individual values of the EC-based hydrograph separation results need to be interpreted with care and that the EC-based maximum event water contributions for the largest events (as shown in Figure 10) are likely overestimated.

An increase in the maximum event water contribution to streamflow with increasing event size (Figure 10; but see also the differences for Manobo in Figures 6 and 7) has been shown previously for other catchments (Fischer et al., 2017; James & Roulet, 2009; Penna et al., 2015; Segura et al., 2012). However, some of these studies did not observe the asymptotic relationship between event total precipitation and maximum event water contributions to streamflow observed for the Basper and Manobo catchments (Figure 10a). For example, for very wet catchments with low-permeability clay soils in Switzerland, the relations between maximum event water contribution and event total precipitation were linear up to 84 mm of event total precipitation (Fischer et al., 2017). Using EC and isotope data in a more seasonally wet montane catchment in northern Italy, Penna et al. (2015) showed that the average and maximum event water contributions increased with event size according to a similar asymptotic relation, but constant event contributions were only reached for events >25–50 mm, much larger than the ~10-mm threshold derived for the Basper catchment.

The maximum event water contributions increased with precipitation intensity at both sites but much more quickly and for lower intensities for the Basper grassland catchment than the Manobo reforestation catchment (Figure 10b). This is likely due to the occurrence of overland flow at Basper, which is more widespread during high-intensity events (which is corroborated by the stronger dependence of peak flow on the maximum precipitation intensity for Basper; Figure 5). In the very wet and responsive Babinda catchments in Northeast Australia, event water contributions were larger for an event with high precipitation intensity than for an event with low intensity because hillside saturated overland flow was much more widespread during the high-intensity event (Elsenbeer et al., 1995). Fischer et al. (2017) showed for the wet and responsive Alptal catchments in Switzerland (where water tables are close to the surface) that maximum event water contributions increased linearly with rainfall intensity (but their maximum hourly rainfall intensity of 18 mm/hr was much lower than in this study).

Maximum event water contributions also increased with increasing antecedent wetness conditions for the Basper grassland catchment (Figure S4b in the supporting information), suggesting more widespread overland flow when soil storage capacity is lower. However, this effect was much smaller than the effect of event size, suggesting that the available storage is small and quickly filled by precipitation. Conversely, antecedent conditions did not affect the maximum event water contributions for the Manobo reforested catchment. However, we did not study events during the driest part of the year (April–May), and therefore, it is still possible that antecedent conditions do affect event water contributions to streamflow for the Manobo catchment. Fischer et al. (2017) found no correlation between event water contributions and antecedent wetness conditions for the very wet Alptal catchments. Contrary, several other studies have reported that event water contributions to streamflow are higher for dry antecedent conditions and that these contributions decrease as the catchment wets up (Litt et al., 2015; McGlynn & McDonnell, 2003). This is generally attributed to the relatively large contribution of direct channel precipitation and overland flow from near-stream areas during dry conditions and a lack of contributions from the hillslopes, where precipitation water replenishes soil moisture storage. The contribution of direct precipitation becomes relatively less as the surrounding soil becomes wetter, groundwater levels rise, and soil and groundwater drainage increase. The lower event water contributions with increasing wetness conditions are also assumed to reflect the gradual increase in connectivity of the hillslopes and streams (Muñoz-Villers & McDonnell, 2013; Sidle et al., 2000).

6. Conclusion

We compared the runoff response of a degraded *Imperata* grassland catchment and a semimature multispecies reforested catchment. In the degraded grassland catchment, streamflow increased, and stream water EC decreased in response to almost all rainfall events. In the reforested catchment, streamflow and EC only changed in response to large events. In both catchments, streamflow was a mixture of groundwater and precipitation, but the fraction of precipitation was much smaller for the reforested catchment than for the degraded catchment. EC-based estimates of the maximum event water contributions were much larger and increased more rapidly with event size for the degraded grassland catchment than for the reforested catchment. The fast and large streamflow responses, large changes in EC and large event water contributions to streamflow, and the low surface saturated hydraulic conductivity suggest that overland flow is widespread in the degraded grassland catchment. The higher surface saturated hydraulic conductivity, longer lag times, smaller runoff ratios (except for the largest event), and smaller event water contributions for the Manobo reforested catchment suggest that streamflow is dominated by subsurface stormflow. These results thus suggest that reforestation can substantially improve infiltration, reduce overland flow, and improve streamflow regulation, provided that the forest and soil are allowed to develop over a sufficiently long period without disturbance. The differences in the peak flow rates, centroid lag time, and isotope-based event water contributions to streamflow were also observed during a very large tropical storm, suggesting that the large differences in runoff generation mechanisms between the two catchments also persist for the largest events.

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